

# EQUIVALENCE PRINCIPLE TESTS AND NEW LONG-RANGE FORCES

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## ABSTRACT

We discuss the possible existence of new long-range forces mediated by spin-1 or spin-0 particles. They would add their effects to those of gravity, and could lead to *apparent* violations of the Equivalence Principle. Informations on the (vector and axial) couplings of a new spin-1  $U$  boson may be obtained from spontaneously broken gauge invariance. The charge associated with the vector coupling may be expressed as a linear combination of  $B$  and  $L$ . If the new force has a finite range  $\lambda$ , its intensity turns out to be proportional to  $1/(\lambda^2 F^2)$ ,  $F$  being the extra  $U(1)$  symmetry-breaking scale.

Quite surprisingly, particle physics experiments can provide constraints on such a force, even if the corresponding gauge coupling is extremely small ( $\ll 10^{-19}$ !). An “equivalence theorem” shows that a very light spin-1  $U$  boson with non-vanishing axial couplings does not in general decouple even when its gauge coupling vanishes, but behaves as a quasimassless pseudoscalar. (This equivalence theorem is similar to the one of supersymmetry/supergravity theories, according to which a very light spin- $\frac{3}{2}$  gravitino might get detectable as a quasi massless spin- $\frac{1}{2}$  goldstino, despite the extreme smallness of Newton’s gravitational constant  $G_N$ .) Searches for the radiative production of such  $U$  bosons in  $\psi$  and  $\Upsilon$  decays restrict the extra  $U(1)$  symmetry-breaking scale  $F$  to be larger than the electroweak scale, providing constraints on the intensity of the corresponding new force.

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# 1 GENERAL OVERVIEW.

Why to test the Equivalence Principle? Could new long-range forces exist, in addition to gravitational and electromagnetic ones, and what could be their properties?

The Equivalence Principle is at the basis of the theory of General Relativity. Although we have no reason to believe that general relativity is incorrect, it is certainly not a satisfactory, complete theory. In particular there is a well-known clash between general relativity and quantum physics. More precisely, no consistent quantum theory of gravity exists, although one hopes to progress towards a solution within the framework of superstring and membrane theories. While the problem may be ignored temporarily for gravitational interactions of particles at physically accessible energies, it becomes crucial at very high energies of the order of the Planck energy,  $\simeq 10^{19}$  GeV. This is the energy scale (corresponding in quantum physics to extremely small distances  $\sim L_{\text{Planck}} \simeq 1.6 \cdot 10^{-33}$  cm) at which gravity is normally expected to become a strong interaction, so that quantum effects, still ill-defined, become essential. At such energies gravity has an effective intensity comparable to that of the three other interactions, strong, electromagnetic and weak. This is where a unification of all four interactions might conceivably occur.

Independently of gravity, the Standard Model of strong, electromagnetic and weak interactions is very successful in describing the physics of elementary particles and their fundamental interactions. But it also suffers from certain difficulties, and leaves a number of questions unanswered. To mention a few:

- it has about 20 arbitrary parameters, including the three gauge couplings of  $SU(3) \times SU(2) \times U(1)$ , two parameters  $\mu^2$  and  $\lambda$  ultimately fixing the  $W$  and Higgs boson masses, and thirteen mass and mixing-angle parameters associated with the quark and lepton spectrum.

- it sheds no light on the origin of the various symmetries and of symmetry breaking, nor on the family problem (why three generations of quarks and leptons, ...).

- in the presence of very large mass scales it suffers from the problem of the stability of the mass hierarchy: how can the  $W$  mass remain so small compared to the grand-unification or the Planck scales, in spite of radiative corrections which would tend to make it of the same order as  $m_{\text{GUT}}$  or  $m_{\text{Planck}}$ ?

- another problem concerns the vacuum energy, when coupled to gravity: unless it is zero or almost zero (i.e. really extremely small, when measured with the natural units of particle physics, even more in terms of Planck's units), it tends to generate a much too large value of the cosmological constant  $\Lambda$ , exceeding by many orders of magnitude what is experimentally allowed ( $|\Lambda| < 3 \cdot 10^{-56} \text{ cm}^{-2} \simeq 10^{-121} L_{\text{Planck}}^{-2}$ !).

- a delicate question concerns the symmetry or asymmetry between Matter and Antimatter. The  $CP$  symmetry is almost a symmetry of all interactions, but it is

violated by some weak interaction effects observed in kaon decays. Then it has no reason to be an exact symmetry of strong interactions, so that the neutron should acquire an electric dipole moment. Since no such moment has been found the corresponding amount of  $CP$ -violation (measured by the dimensionless parameter  $\theta_{\text{eff}}$ ) should be smaller than  $\approx 10^{-9}$ , already a very small number. A possible mechanism to understand this requires the existence of a new neutral, very light, spin-0 particle, the axion (Wilczek, 1978; Weinberg, 1978).

Essentially all attempts to go beyond the Standard Model and try to bring a solution to the above problems involve the introduction of *new symmetries*, *new particles*, and therefore quite possibly *new forces*.

Such a situation already occurred thirty years ago, when the problems associated with the non-renormalisability of known (charged-current) weak interactions led physicists to rely on the new gauge symmetry principle, and to postulate the existence of a new particle, the neutral gauge boson  $Z$ , in addition to the (then still hypothetical) charged ones,  $W^+$  and  $W^-$ . This finally led to what is known as the Standard Model. The  $Z$  mass had to be of the same order as the  $W$  mass,  $Z$ -exchanges being responsible for a new class of weak-interaction effects (through “neutral currents”) that were subsequently discovered in 1973, ten years before the  $W$ ’s and  $Z$ ’s could be directly produced at CERN, in 1983. The corresponding new force has a very small range of about  $2 \cdot 10^{-16}$  cm, as for charged-current weak interactions. It is now conceivable (and even likely) that the solution to the problems associated with the quantization of gravity requires the existence of new particles – in addition to the usual massless spin-2 graviton – and therefore of new forces, possibly long-ranged, appearing as additions or modifications to the known force of gravity.

Irrespectively of gravitation, the grand-unification between electroweak and strong interactions would involve very heavy spin-1 gauge bosons that could be responsible for proton decay. The supersymmetry between bosons and fermions requires the existence of new superpartners for all particles. These new particles – together with the two Higgs doublets required for electroweak breaking within supersymmetry – have a crucial effect on the evolution of the weak, electromagnetic and strong gauge couplings, allowing them to converge, at a large value of the grand-unification energy scale of the order of  $10^{16}$  GeV. Supersymmetry is also closely related with gravitation, since a locally supersymmetric theory must be invariant under general coordinate transformations. And the lightest of the new superpartners predicted by supersymmetric theories, which all have an odd  $R$ -parity character (with  $R$ -parity equal to  $(-1)^{2S} (-1)^{3B+L}$ ) turns out to be an almost ideal candidate to constitute the non-baryonic Dark Matter that seems to be present in the Universe.

More ambitious theories involve extended supersymmetry, new compact space dimensions of various kinds, and extended objects like superstrings and membranes,

aiming at a completely unified description of all interactions, including gravity. They involve many new particles, including in general new neutral spin-1 or spin-0 bosons appearing as lower-spin partners or companions of the spin-2 graviton, etc.. The exchanges of such new particles could lead to new forces adding their effects to those of gravity. They could manifest experimentally through (apparent) violations of the Equivalence Principle – according to which the gravitational and inertial masses may be identified – since what seems to be, experimentally, the force of gravity, might in fact be the superposition of gravity itself (acting proportionally to masses) with some other additional new force(s) having different properties.

In particular, spin-1 bosons hereafter called *U*-bosons could gauge extra  $U(1)$  symmetries (cf. Fayet, 1990), as will be discussed in more details below. *U*-exchanges would be responsible for a new force involving the *vector* part in the *U* current, and expected to act on ordinary matter in an *additive* way, proportionally to a linear combination of the numbers of protons and neutrons,  $Z$  and  $N$ , as we shall see. If the *U* boson is massless or almost massless with an extra  $U(1)$  gauge coupling  $g$  extremely small, the new force would superpose its effects to those of gravitation, leading to *apparent violations of the Equivalence Principle*, since the numbers of neutrons and protons in an object are not exactly proportional to its mass. Newton’s  $1/r^2$  law of gravitation could also appear to be violated, if the new force has a finite range.

The spin-0 dilaton (or “moduli”, etc.) fields originating from superstring scenarios may well (or even should) remain massless; they are then generally expected to lead to excessively large deviations from the Equivalence Principle. However these fields could have their vacuum expectation values attracted towards a point at which they would almost decouple from matter (Damour and Polyakov, 1994). Their residual interactions could then be detected through extremely small (apparent) violations of the Equivalence Principle, possibly at a level estimated to be of the order of  $10^{-12}$  to  $10^{-24}$ .

The Equivalence Principle has already been tested to a very good level of precision, of about a few  $10^{-12}$  at large distances (Roll et al., 1964; Adelberger et al., 1990; Su et al., 1994). Lunar laser ranging data also indicate that the acceleration rates of the (Fe/Ni-cored) Earth and the (silicate-dominated) Moon towards the Sun are practically equal, to a level of precision slightly better than  $10^{-12}$  (cf. Williams et al., 1996; Müller et al., 1997; Müller and Nordtvedt, 1998). Strictly-speaking the interpretation of this result, however, also involves the consideration of gravitational-binding energies, in addition to the different compositions of the Earth and the Moon.

The sensitivity of Equivalence Principle tests could be further improved by monitoring the relative motion of two test masses of different compositions, circling around the Earth, in a drag-free satellite. The MICROSCOPE experiment (“MicroSatellite à

Compensation de traînée pour l’Observation du Principe d’Equivalence”), whose construction has just been decided by CNES, aims at testing the validity of this principle at a level of precision of  $10^{-15}$  (Touboul, 2000). The STEP experiment (“Satellite Test of the Equivalence Principle”) is a more ambitious project which aims at a level of sensitivity that could reach  $\sim 10^{-17} - 10^{-18}$  (Blaser et al., 1996; Vitale, 2000), a considerable improvement by five orders of magnitude or more compared to the present situation.

The test masses, incidentally, cannot be taken spherical, but only cylindrical. A potential difficulty is the existence of residual interactions between the higher multipole moments of the test masses and the gravity gradients induced by disturbing masses within the satellite, which could lead to an unwanted signal simulating a “violation of the Equivalence Principle”. To minimize these effects one can use test masses approaching ideal forms of “aspherical gravitational monopoles”, which are homogeneous solid bodies for which *all higher multipole moments vanish identically*, despite the lack of spherical symmetry (Connes et al., 1997)!

Should deviations from the Equivalence Principle be observed, further informations relying on data from several differential accelerometers could allow one to distinguish between new spin-1 or spin-0 induced forces, adding their effects to those of gravity. In the first case the new force is generally expected to act on a linear combination of baryon and lepton numbers  $B$  and  $L$  (which coincides in practice with a combination of the numbers of protons and neutrons,  $Z = L$  and  $N = B - L$ ). For spin-0 exchanges the new force may be expected to act effectively on a linear combination of  $B$  and  $L$  with electromagnetic (and chromodynamics) energies. Should such a force be found, testing several pairs of bodies of different compositions could allow one to distinguish between the spin-1 and spin-0 cases.

## 2 GENERAL FEATURES OF A NEW SPIN-1 INDUCED FORCE.

### 2.1 Possible extra $U(1)$ gauge symmetries.

For spin-1 particles we can rely on the general principle of gauge invariance to determine the possible couplings of a spin-1  $U$ -boson, and the expected properties of the corresponding force, should it exist (Fayet, 1990). To do so we first identify the possible extra  $U(1)$  symmetries of a Lagrangian density, which are potential candidates for being gauged. This turns out to depend crucially on the number of Higgs doublets responsible for the electroweak breaking. In the Standard Model there is no other  $U(1)$  symmetry than those associated with the conservations of baryon and lepton numbers ( $B$  and  $L_i$ ), and with the weak hypercharge  $Y$  generating the  $U(1)$  subgroup of  $SU(2) \times U(1)$ . More generally, in any renormalizable theory with only

one Higgs doublet, any  $U(1)$  symmetry generator  $F$  must act on quarks and leptons as a linear combination:

$$F = \alpha B + \beta_i L_i + \gamma Y \quad . \quad (1)$$

Supersymmetric theories, however, require two Higgs doublets. This leaves room for an additional  $U(1)$  invariance, since we may now perform independent phase rotations on these two doublets. With two Higgs doublets separately responsible for up-quark masses ( $h_2$ ), and down-quark and charged-lepton masses ( $h_1$ ), we now get:

$$F = \alpha B + \beta_i L_i + \gamma Y + \mu F_{ax} \quad , \quad (2)$$

$F_{ax}$  being an extra  $U(1)$  generator corresponding to a symmetry group  $U(1)_A$  acting *axially* on quarks and leptons. This  $U(1)_A$  itself or, more generally, an extra  $U(1)$  generated by a linear combination as in (2) was gauged, in the first supersymmetric models of 1976-1977, to trigger spontaneous supersymmetry breaking without having to resort to soft supersymmetry-breaking terms<sup>2</sup>. Such models provided, very early, a natural framework for a possible new long-or-intermediate-range “fifth force” (Fayet, 1980, 1981, 1986a, 1986b), which may now be considered, independently of supersymmetry (for which, in any case, other methods of supersymmetry breaking are now generally employed). Furthermore, in grand-unified theories with large gauge groups including  $SU(5)$  or  $O(10)$ , quarks are related to leptons, so that  $B$  and  $L$  no longer appear separately, but only through their difference  $B-L$ . The general form of an extra  $U(1)$  symmetry generator that could be gauged is then given by:

$$F = \eta \left( \frac{5}{2} (B - L) - Y \right) + \mu F_{ax} \quad . \quad (3)$$

## 2.2 Expression of the new “charge” $Q_5$ .

To know on which quantity the new force should really act (still within the framework of a renormalizable theory), we also have to take into account mixing effects between neutral gauge bosons. The resulting  $U$  current involves a linear combination of the extra- $U(1)$  current identified previously, with the  $Z$  weak neutral current  $J_Z = J_3 - \sin^2 \theta J_{em}$ . For simple Higgs systems the extra- $U(1)$  generator, and subsequently the  $U$ -current, does not depend on the quark generation considered. The new force should then act on quarks in a flavor-conserving and generation-independent way. There should be no couplings to strangeness, charm or beauty, nor on mass itself either (in which case no “deviation from the Equivalence Principle” would have to be expected). Couplings to a linear combination of  $B$  and  $L$  with the electrical

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<sup>2</sup>This, however, also raised the delicate question of anomaly cancellation, although anomalous  $U(1)$ ’s might possibly be tolerated after all ...

charge  $Q$ , as well as couplings involving particle spins, are expected instead (Fayet 1986a, 1986b, 1990). They will originate from the *vector* and *axial* parts in the  $U$  current, respectively.

The vector part in the  $U$  current is found to be a linear combination of baryonic and leptonic currents with the electromagnetic current, associated with the (normally conserved) charge

$$Q_5 = x B + y_i L_i + z Q_{el} \quad , \quad (4)$$

which reduces to

$$Q_5 = x (B - L) + z Q_{el} \quad , \quad (5)$$

in the framework of grand-unification. Even if the new force acts in general on electrons as well as on protons and neutrons, the above formulas further simplify, for ordinary neutral matter, into

$$Q_5 = x B + y L = x (N + Z) + y Z \quad , \quad (6)$$

or, in grand-unification, to

$$Q_5 = x (B - L) = x N \quad . \quad (7)$$

The action of such a spin-1-induced fifth force on neutral matter may then be written in an additive way, proportionally to a linear combination of the numbers of protons (and electrons) and neutrons,  $Z$  and  $N$ . This is of course not true for the gravitational force itself, and has no reason to be true in the case of a force induced by spin-0 exchanges. (As an illustration, this means, for example, that the  $U$ -induced force acting on a helium-4 atom should be twice the force acting on a deuterium atom – while the mass of this helium-4 atom differs from twice the mass of a deuterium atom.) In the framework of grand-unification,  $B$  and  $L$  only appear through their difference so that the new force is expected to act effectively on neutrons only. When the  $U$  boson is massless or almost massless and the extra  $U(1)$  gauge coupling is extremely small, one expects (very small) violations of the Equivalence Principle, since the numbers of neutrons and protons in an object are not exactly proportional to its mass.

Should such a force be discovered, its properties may be used to test its origin, and whether it is due to spin-1 or spin-0 particles, for example, since a spin-0 induced force has no reason to act additively, precisely on a linear combination of  $B$  and  $L$  (not to mention the very specific combination  $B - L$  which could appear in grand-unified theories).

## 2.3 A relation between range and intensity ?

The next things one would like to know are, of course, the possible *range* of the new force and its expected *intensity*, relatively to gravity.

The range could be infinite if the  $U$  boson stays massless. This occurs for example if there is only a single Higgs doublet (and no other Higgses), so that the  $SU(3) \times SU(2) \times U(1) \times \text{extra-}U(1)$  gauge group gets broken down to  $SU(3) \times U(1)_{QED} \times U(1)_{U\text{-boson}}$ , the  $U$  boson remaining exactly massless and coupled to a linear combination of the conserved  $B$ ,  $L$  and electromagnetic currents (Fayet, 1989). The intensity of the new force, determined by the value of the extra  $U(1)$  gauge coupling constant  $g''$ , remains, at this stage, essentially arbitrary. It might be extremely small, especially if the extra  $U(1)$  turns out to be linked in some way with gravitational interactions.

In general, however, both the range of the new force and its possible intensity appear as largely arbitrary. Still *for any given symmetry breaking scale  $F$*  these two quantities turn out to be related as follows:

“the longer the range  $\lambda$ , the smaller the expected intensity”.

The origin of this interesting relation is in fact not mysterious. The  $U$  boson mass – when it does not vanish – determines the range of the corresponding force by the usual formula of quantum physics:

$$\lambda = \frac{\hbar}{m_U c} \simeq 2 \text{ meters} \frac{10^{-7} \text{ eV}/c^2}{m_U} . \quad (8)$$

Large masses  $\gtrsim 200 \text{ GeV}/c^2$  – well within the domain of particle physics – would correspond to extremely short ranges  $\lambda \lesssim 10^{-16} \text{ cm}$ , less than the range of weak interactions. On the other hand very small masses of  $10^{-10} \text{ eV}/c^2$  or less, for example, would lead to large macroscopic ranges of 2 kilometers or more. The new force would then superpose its effects to those of gravitation, leading to apparent violations of the Equivalence Principle; and also, depending on the range, to apparent deviations from Newton’s  $1/r^2$  law of gravitation.

Let us now turn to the *intensity* of the new force, considered relatively to gravity. It may be characterized, at distances larger than the range  $\lambda$ , by the dimensionless ratio

$$\tilde{\alpha} \approx \frac{\left(\frac{g''}{4}\right)^2 / 4\pi}{G_{\text{Newton}} m_{\text{proton}}^2} \approx 10^{36} g''^2 , \quad (9)$$

$g''$  being the extra- $U(1)$  gauge coupling constant, a priori unknown but which may be extremely small (especially, again, if the extra  $U(1)$  symmetry turns out to be linked in some way with gravity itself). The  $U$  mass is related to the extra- $U(1)$  symmetry-breaking scale  $F$ , determined by the appropriate Higgs v.e.v.’s, by a relation which may be written as

$$m_U \approx g'' \frac{F}{2} . \quad (10)$$



For a given scale  $F$ , the relative intensity of the new force then behaves like

$$\tilde{\alpha} \sim g''^2 \sim \frac{m_U^2}{F^2} \sim \frac{1}{\lambda^2 F^2} \quad , \quad (11)$$

or, more precisely, with an uncertainty reflecting the effects of the model-dependent factors in the coefficients (Fayet, 1986a, 1986b):

$$\tilde{\alpha} \approx \frac{1}{\lambda_{(\text{meter})}^2} \left( \frac{250 \text{ GeV}}{F} \right)^2 \quad . \quad (12)$$

This relation looks very nice, but before we can really use it we must know or assume something about the symmetry-breaking scale  $F$ . Before discussing this point in the next sections, let us assume for the moment, as an illustration, that the extra  $U(1)$  is broken at or around the electroweak scale ( $\approx 250 \text{ GeV}$ ), a natural benchmark in particle physics. We would then get for small (or moderate) values of the range  $\lambda$ , rather large (or not so small) values of  $\tilde{\alpha}$ , e.g.

$$\tilde{\alpha} \approx \begin{cases} 10^7 - 10^9 & \text{if } \lambda \simeq 10^{-1} \text{ mm} \quad , \\ 10^{-3} - 10^{-5} & \text{if } \lambda \simeq 100 \text{ m} \quad , \end{cases} \quad (13)$$

values which are already forbidden by existing gravity experiments including those performed at short distances (Hoskins et al., 1985; Mitrofanov and Ponomareva, 1988; Adelberger et al., 1990; Su et al., 1994; Lamoreaux, 1997; Schmidt et al., 2000; Hoyle et al., 2001), which imply, for example, that  $\tilde{\alpha}$  should be smaller than  $10^{-1}$  for ranges  $\lambda \gtrsim 1 \text{ mm}$ ). This corresponds to the fact that in such cases the new extra  $U(1)$  gauge coupling  $g''$  is not so small compared to  $10^{-19}$  or even significantly larger in the case of a small  $\lambda$ , so that the new force is not so small compared to gravity or may even dominate it at small distances.

On the other hand we would have

$$\tilde{\alpha} \approx \begin{cases} 10^{-5} - 10^{-7} & \text{if } \lambda \simeq 1 \text{ km} \quad , \\ 10^{-11} - 10^{-13} & \text{if } \lambda \simeq 10^3 \text{ km} \quad , \end{cases} \quad (14)$$

the latter case, which would lead to apparent violations of the Equivalence Principle at the level of  $10^{-13}$  to  $10^{-16}$ , being within the reach of the future MICROSCOPE and STEP experiments – sensitive only to ranges  $\lambda$  larger than a few hundreds of kilometers, given the elevation at which the satellite should orbitate. But, as we have already indicated, these estimates for  $\tilde{\alpha}$  depend crucially on what the extra- $U(1)$  symmetry breaking scale  $F$  is. Could there be some way to learn something about it?

No one would imagine, under normal circumstances, being able to search directly for ordinary massless *gravitons* in a particle physics experiment, due to the extremely

small value of the Newton constant ( $10^{-38}$ , in units of  $\text{GeV}^{-2}$ ), which determines the strength of the couplings of a single massless graviton to matter. Then how could we search directly, in particle decay experiments, for  $U$ -bosons with even smaller values of the corresponding coupling,  $g''^2 \ll 10^{-38}$ ? Still this turns out to be possible! This rather astonishing result holds as soon as the  $U$ -current includes a (non-conserved, as the result of spontaneous symmetry breaking) *axial* part, as we shall see. The origin of this phenomenon involves an “equivalence theorem” between the interactions of spin-1 gauge particles and those of spin-0 particles, in the limit of very small gauge couplings.

### 3 “EQUIVALENCE THEOREMS” FOR SPIN-1 AND SPIN- $\frac{3}{2}$ PARTICLES.

#### 3.1 A very light spin-1 $U$ boson does *not* decouple for vanishing gauge coupling – but behaves like a spin-0 particle!

One might think that, in the limit of vanishing extra- $U(1)$  gauge coupling constant  $g''$ , the effects of the new gauge boson would be arbitrarily small, and may therefore be disregarded (as for graviton effects in particle physics). But in general this is *wrong*, as soon as the  $U$ -current involves a (non-conserved) axial part – which is generally the case when a second Higgs doublet is present to break the electroweak symmetry, as in supersymmetric theories!

The amplitudes for emitting a very light ultrarelativistic  $U$  boson are proportional to the new gauge coupling  $g''$ , and therefore seem to vanish with  $g''$ . This is, however, misleading, since the polarization vector for a longitudinal  $U$  boson of four-momentum  $k^\mu$ ,  $\epsilon^\mu \simeq k^\mu/m_U$ , becomes singular in this limit, since  $m_U \approx g'' F/2$  also vanishes with  $g''$ . Altogether the amplitudes for emitting, or absorbing, a longitudinal  $U$  boson, appear to be essentially proportional to  $g''/m_U$ . They have a finite limit, *independent of  $g''$* , when this gauge coupling becomes very small and the mass of the  $U$  boson gets also very small, so that this  $U$  boson is ultrarelativistic (i.e.  $k^\mu \gg m_U$ ). Such a  $U$  boson then behaves very much like a spin-0 particle (Fayet 1980, 1981), somewhat reminiscent of an axion.

This “equivalence theorem” expresses that in the high-energy or low-mass limit ( $E \gg m_U$ ), the third (longitudinal) degree of freedom of a massive  $U$ -boson continues to behave like the massless Goldstone boson which was “eaten away”. For very small  $g''$  the spin-1  $U$ -boson simply behaves as this massless spin-0 Goldstone boson. This applies as well to virtual exchanges. The exchanges of the  $U$  boson do not disappear in this limit, owing to the non-conserved axial part in the  $U$  cur-

rent (in general present when there is more than one Higgs doublet). They become equivalent to the exchanges of a massless (pseudoscalar,  $CP$ -odd) spin-0 particle  $a$ , having effective axionlike couplings to leptons and quarks

$$2^{1/4} G_F^{1/2} m_{l,q} (x \text{ or } 1/x) \times \left( r \approx \frac{250 \text{ GeV}}{F} \right) \gamma_5, \quad (15)$$

$x$  denoting the ratio of the two Higgs doublet vacuum expectation values. Using notations which are standard in supersymmetry<sup>3</sup>, where the first Higgs doublet is responsible for down-quark and charged-lepton masses, and the second one for up-quark masses, one has  $1/x = v_2/v_1 = \tan \beta$ . More precisely, these effective pseudoscalar couplings to quarks and leptons read

$$\underbrace{2^{1/4} G_F^{1/2} m_{l,q} \left\{ \begin{array}{ll} x \text{ (i.e. } 1/\tan \beta) & \text{for } u, c, t \text{ quarks} \\ 1/x \text{ (i.e. } \tan \beta) & \text{for } \left\{ \begin{array}{l} d, s, b \text{ quarks} \\ e, \mu, \tau \text{ leptons} \end{array} \right. \end{array} \right\}}_{\text{as for a standard axion}} \times \left( r \approx \frac{250 \text{ GeV}}{F} \right),$$

as for an “invisible” axion, if  $r \ll 1$

(16)

From there one can get, from particle physics, constraints on such a new spin-1 gauge boson, as we shall discuss in section 4. They will require the extra  $U(1)$  symmetry-breaking scale  $F$  to be larger than the electroweak scale. Note that the *transverse* polarization states of the  $U$ -boson still continue to behave as usual, and would be responsible, for small but non-vanishing  $g$ , for a very weak long-ranged “EP-violating” force, of intensity proportional to  $g^2$ , to which we shall return in section 4.

### 3.2 Increasing the symmetry-breaking scale $F$ (“invisible $U$ -boson” and “invisible axion” mechanisms).

If the extra  $U(1)$  gauge symmetry is broken at the electroweak scale ( $F \approx 250 \text{ GeV}$ ) by the two Higgs doublets  $h_1$  and  $h_2$  only, the spin-1  $U$ -boson acquires, from its non-vanishing axial couplings, exactly the same effective pseudoscalar couplings (16) as a “standard” spin-0 axion (i.e.,  $r \equiv 1$ ). Just as the latter, it then turns out to be excluded by the results of  $\psi$  and  $\Upsilon$  decay experiments, i.e. searches for the decays  $\psi \rightarrow \gamma + \text{“nothing”}$ ,  $\Upsilon \rightarrow \gamma + \text{“nothing”}$ , in which “nothing” stands for a quasimassless neutral spin-1 particle (the  $U$ -boson), or a spin-0

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<sup>3</sup>The pseudoscalar  $a$ , here eaten away to become the third (longitudinal) degree of freedom for the massive  $U$  boson, is of course by construction reminiscent of the well-known pseudoscalar  $A$  of supersymmetric extensions of the standard model, which becomes the Goldstone boson of the  $U(1)_A$  invariance when this one is taken as a symmetry of the Lagrangian density.

particle (such as the axion), remaining undetected in the experiments. *Exit* such a  $U$  boson, and therefore the corresponding new force that could be due to  $U$ -boson exchanges?

Not necessarily! As we observed in 1980, to save the possibility of such a light  $U$  boson (or just as well, to save the idea of the axion), one can introduce an extra Higgs singlet acquiring a large v.e.v.  $\gg 250$  GeV, which would make the  $U$  boson significantly heavier (but still remaining light!) without modifying the values of its (vector and axial) couplings to ordinary quarks and leptons. Its effective interactions with quarks and leptons, fixed by the ratio of the axial couplings – proportional to  $g''$  – to the mass  $m_U$ , may then become arbitrarily small, as one sees easily from the expression (16) of the resulting effective pseudoscalar couplings to quarks and leptons. The mechanism, which involves for the effective interaction of the  $U$  boson, or of its equivalent pseudoscalar  $a$ , the suppression factor  $r \approx F/250 \text{ GeV} \ll 1$ , allows for making the  $U$  boson effects in particle physics practically “invisible”, provided the extra  $U(1)$  is broken “at a large scale”  $F$  significantly higher than the electroweak scale.

Incidentally since a spin-1  $U$ -boson, when very light, is produced and interacts very much as a spin-0 pseudoscalar axionlike particle (excepted that it does not decay into two photons), the mechanism we explained also provided us, at the same time, with a way to make the interactions of the axion almost “invisible”, at least in particle physics (Fayet 1980, 1981). This can be realized by breaking the corresponding global  $U(1)_A$  symmetry, then considered as a Peccei-Quinn symmetry, at a very large scale, through a very large singlet vacuum expectation value, the resulting axion being mostly an electroweak singlet. We thus obtained simultaneously both the “invisible  $U$ -boson” mechanism (for a spontaneously-broken extra  $U(1)$  local gauge symmetry, the case of interest to us here), and the “invisible axion” mechanism (in the case of a global  $U(1)_{PQ}$  symmetry broken at a very high scale) that became popular later (Fayet 1980, 1981; Zhitnisky, 1980; Dine et al. 1981).

### 3.3 The gravitino/goldstino “equivalence theorem” in supersymmetric theories.

The same phenomenon, in the case of local supersymmetry, called supergravity, expresses that a *very light* spin- $\frac{3}{2}$  *gravitino* (the superpartner of the spin-2 graviton, and also the gauge particle of the local supersymmetry), having interactions fixed by the gravitational “gauge” coupling constant  $\kappa = \sqrt{8\pi G_N} \simeq 4.1 \cdot 10^{-19} (\text{GeV})^{-1}$ , would behave very much like a massless spin- $\frac{1}{2}$  *goldstino*, according to the “equivalence theorem” of supersymmetry (Fayet, 1977, 1979). Just as the mass of the  $U$  boson is given in terms of the extra  $U(1)$  gauge coupling  $g''$  and symmetry breaking scale  $F$  by the formula  $m_U \approx g'' F/2$ , the mass of the spin- $\frac{3}{2}$  gravitino is

fixed by its (known) gravitational “gauge” coupling constant  $\kappa$  and the (unknown) supersymmetry-breaking scale parameter  $d$ , as follows:

$$m_{3/2} = \frac{\kappa d}{\sqrt{6}} \simeq 1.68 \left( \frac{\sqrt{d}}{100 \text{ GeV}} \right)^2 10^{-6} \text{ eV}/c^2 . \quad (17)$$

The interactions of a light gravitino are in fact determined by the ratio  $\kappa/m_{3/2}$ , or  $G_N/m_{3/2}^2$ . As a result a sufficiently light gravitino might be detectable in particle physics experiments, despite the extremely small value of the Newton constant  $G_N \simeq 10^{-38} \text{ (GeV)}^{-2}$ , provided the supersymmetry-breaking scale  $\sqrt{d}$  is not too large. The gravitino would then be the lightest supersymmetric particle, with all other  $R$ -odd superpartners expected to ultimately produce a gravitino among their decay products, if  $R$ -parity is conserved. (In particular the lightest neutralino could decay into photon + gravitino, so that the pair-production of “supersymmetric particles” could lead to final states including two photons with missing energy carried away by unobserved gravitinos.)

For a sufficiently light gravitino one can also search for the *direct production* of a single gravitino associated with an unstable photino  $\tilde{\gamma}$  (or more generally a neutralino), decaying into gravitino +  $\gamma$ , in  $e^+e^-$  annihilations. Or for the radiative pair-production of two gravitinos in  $e^+e^-$  or  $p\bar{p}$  annihilations at high energies (Fayet, 1982, 1986c; Brignole et al., 1998a, 1998b), e.g.

$$e^+e^- \text{ (or } p\bar{p}) \rightarrow \gamma \text{ (or jet)} + 2 \text{ unobserved gravitinos} , \quad (18)$$

which have cross-sections

$$\sigma \propto \frac{G_N^2 \alpha \text{ (or } \alpha_s) s^3}{m_{3/2}^4} \propto \frac{\alpha \text{ (or } \alpha_s) s^3}{d^4} . \quad (19)$$

Although the existence of so light gravitinos may appear as relatively unlikely, such experiments are sensitive to gravitinos of mass  $m_{3/2} \lesssim 10^{-5} \text{ eV}/c^2$ , corresponding to supersymmetry-breaking scales smaller than a few hundreds of GeV’s.

## 4 IMPLICATIONS OF PARTICLE PHYSICS EXPERIMENTS.

Without necessarily having to consider very large values of  $F$ , we can use formula (16) (obtained with two Higgs doublets and an axial part in the  $U$ -current) to write

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<sup>4</sup>An equivalent notation makes use of a parameter  $\sqrt{F} = \sqrt{d}/2^{1/4}$ , defined so that  $F^2 = d^2/2$ . Furthermore, the supersymmetry-breaking scale ( $\sqrt{d}$  or  $\sqrt{F}$ ) associated with a (stable or quasistable) light gravitino should in principle be smaller than a few  $10^6 \text{ GeV}$ ’s, for its mass to be sufficiently small ( $m_{3/2} \lesssim 1 \text{ keV}/c^2$ ), so that relic gravitinos do not contribute too much to the energy density of the Universe.

the branching ratios for the radiative production of  $U$  bosons in quarkonium decays, proportionally to  $r^2$  (or  $1/F^2$ ):

$$\begin{cases} B(\psi \rightarrow \gamma + U) \simeq 5 \cdot 10^{-5} \cdot r^2 \cdot x^2 & C_\psi \\ B(\Upsilon \rightarrow \gamma + U) \simeq 2 \cdot 10^{-4} \cdot (r^2/x^2) & C_\Upsilon \end{cases} \quad (20)$$

( $C_\psi$  and  $C_\Upsilon$ , expected to be larger than  $1/2$ , take into account QCD radiative and relativistic corrections). The  $U$  boson, quasistable or decaying into  $\nu\bar{\nu}$ , would remain undetected (as for an axion decaying into two photons outside the detector). From the experimental limits (Edwards et al., 1982; Crystal Ball coll., 1990; CLEO coll., 1995):

$$\begin{cases} B(\psi \rightarrow \gamma + \text{“nothing”}) < 1.4 \cdot 10^{-5} , \\ B(\Upsilon \rightarrow \gamma + \text{“nothing”}) < 1.5 \cdot 10^{-5} , \end{cases} \quad (21)$$

we deduce  $r \lesssim 1/2$ , i.e. that the extra- $U(1)$  symmetry should be broken at a scale  $F$  at least of the order of twice the electroweak scale (Fayet, 1980, 1981, 1986a, 1986b).

This result, obtained for a  $U$  with *non-vanishing axial couplings*, can be translated (assuming vector and axial parts in the  $U$  current to be of similar magnitudes) into an approximate upper bound on the relative strength of the new force, as a function of its range  $\lambda$ :

$$\tilde{\alpha} \approx \frac{\left(\frac{g''}{4}\right)^2 / 4\pi}{G_{Newton} m_{proton}^2} \approx \frac{1}{\lambda(\text{meter})^2} \left(\frac{250 \text{ GeV}}{F}\right)^2 \lesssim \frac{1}{\lambda(\text{meter})^2} . \quad (22)$$

These particular constraints allow for a new force that, if it had a short range, could be very large compared to the gravitational force (e.g. up to  $\tilde{\alpha} \approx 10^6$  for a range  $\lambda \simeq 1$  millimeter, for example), but such large values are already forbidden by short-range gravity experiments (Hoyle et al., 2001). If, on the other hand, the range  $\lambda$  turns out to be large, the constraints (22) become quite significant, and may be used to restrict or even practically exclude the existence of the new force of the special type considered here, whose relative intensity is then experimentally constrained to be rather small. As an illustrative example with  $\lambda = 10^3$  km, we would get  $\tilde{\alpha} \lesssim 10^{-11} - 10^{-13}$ , corresponding to expected violations of the Equivalence Principle

$$\lesssim 10^{-13} - 10^{-16} , \quad (23)$$

with an upper bound still within the sensitivity of the MICROSCOPE and STEP experiments. For significantly larger  $\lambda$ 's, however, the violations are likely to remain undetectable, in the present case of a spin-1  $U$ -boson with non-vanishing axial couplings.

## 5 CONCLUSIONS.

We emphasize that the above constraints of section 4, which are rather drastic in the case of a long-range force, concern the case of a  $U$  boson having non-vanishing axial couplings, on which we have been concentrating here. For a  $U$ -boson coupled to a *purely vectorial* current, on the other hand – or in the case of a new force due to spin-0 exchanges – no such constraints are obtained. Then the strength of the new force and its range (finite or infinite) remain unrelated parameters.

We also mention, in addition, that the exchanges of a new spin-1  $U$  boson, or of a spin-0 particle such as the axion, could lead to new forces acting on particle spins. More precisely one can search for a ( $CP$ -conserving) spin-spin interaction, and a ( $CP$ -violating) “mass-spin coupling” interaction (Moody and Wilczek, 1982; Fayet, 1996), which we do not discuss here.

Very precise tests of the Equivalence Principle could be sensitive to new spin-0 or spin-1 induced forces, and could in principle allow us to distinguish between the two possibilities of spin-0 or spin-1 induced forces. For a spin-1  $U$  boson with non-vanishing axial couplings the intensity of the new force is in general constrained to be extremely weak if it is long-ranged, otherwise it remains essentially a free parameter. Testing, to a very high degree of precision, the Equivalence Principle in Space would bring new constraints on Fundamental Physics, and might conceivably lead to the spectacular discovery of a new long-ranged interaction, should a deviation from this Principle be found.

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